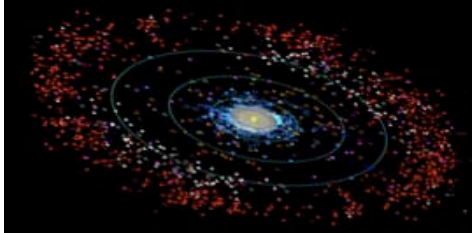
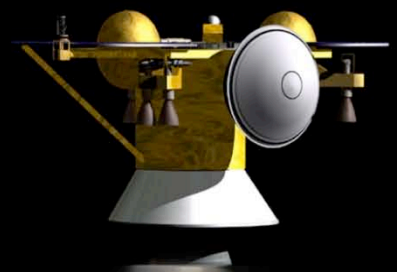
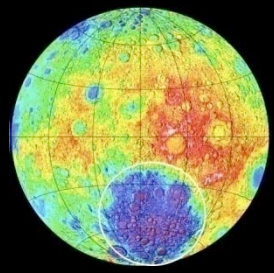


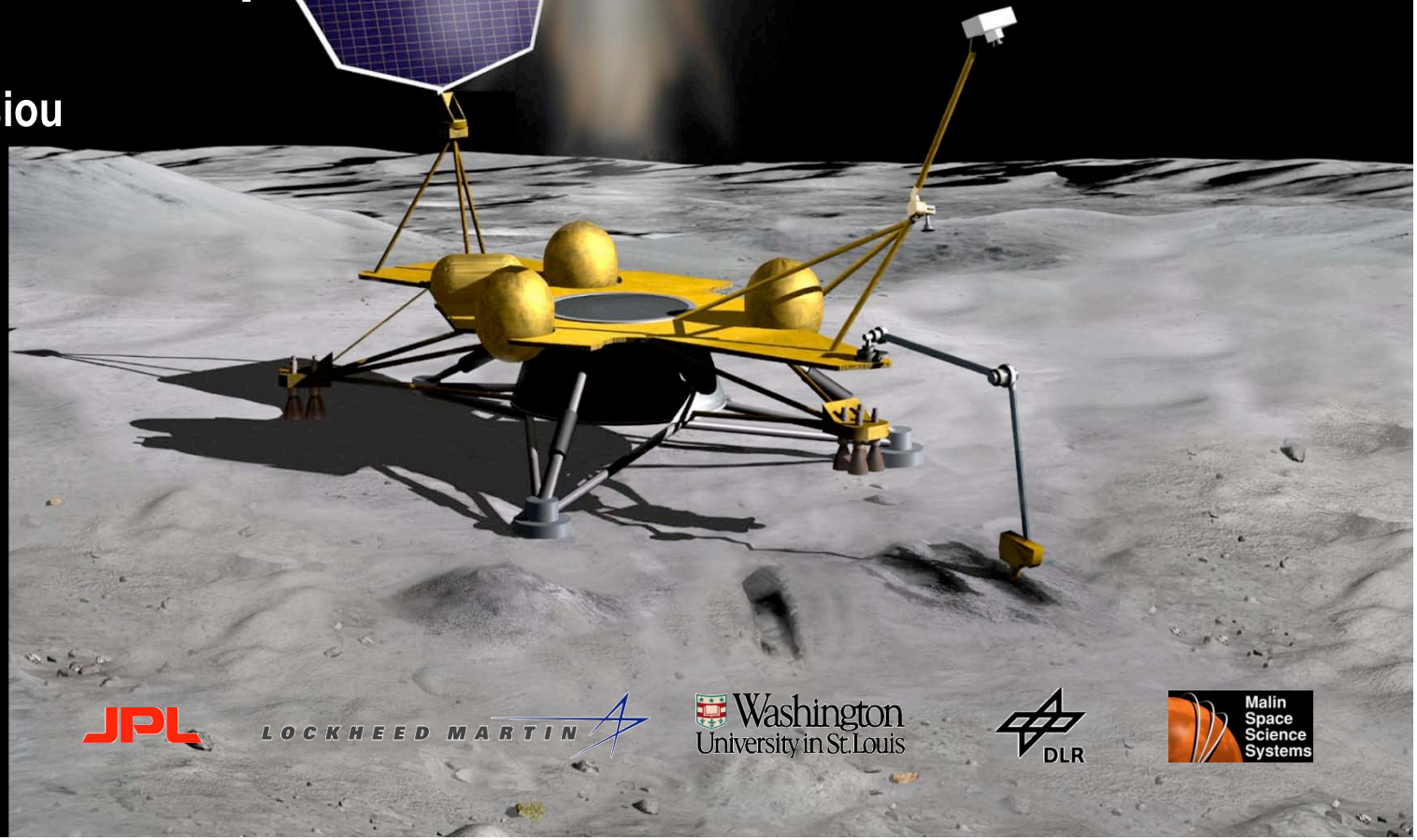




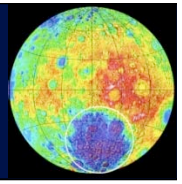
MoonRise

Re-determining Rb-Sr ages of Apollo 16 impact melt rocks: Implications for sample return from SPA

D. A. Papanastassiou
L. E. Nyquist
C.-Y. Shih
Y. D. Reese
R. L. Korotev
B. L. Jolliff
B. A. Cohen

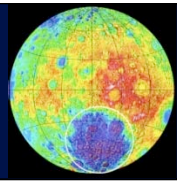


Summary of MoonRise Talks at the NLSI Lunar Forum



- MoonRise sample return from the South Pole-Aitken Basin. *Jolliff et al., Poster, July 21, 3:30 pm*
- Re-determining Rb-Sr ages of Apollo 16 impact melt rocks: Implications for sample return from SPA. *Papanastassiou et al., Talk, July 21, 3:30 pm*
- Analysis of samples from regolith in the Moon's South Pole-Aitken Basin, using basalts to probe the interior of the Moon. *Shearer et al., Talk July 21, 3:45 pm*
- Geologic context for lunar sample return: the MoonRise context imager. *Jaumann et al., Poster July 21, 3:30 pm*
- *Also of interest, SPA Talk*: Compositional diversity in the South Pole-Aitken Basin (SPA) as viewed by the Moon Mineralogy Mapper (M^3). *Petro et al., Talk July 22, 11:30 am*

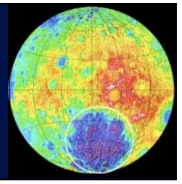
MoonRise: Key Goal



- Determination of the age of the South Pole-Aitken basin is key to addressing the evolution of the Solar System with respect to:
  - –The Lunar Terminal Cataclysm hypothesis

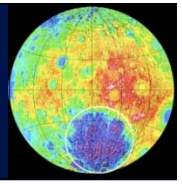
    and
  - –The Nice model for the re-arrangement of the orbits of the giant planets, which then rained comets and asteroids (with different time constants) into the inner solar system

MoonRise: Analytical Capabilities



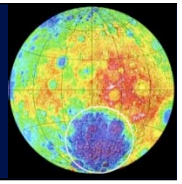
- We address the analytical capabilities required for age dating and demonstrate that current capabilities are well suited to dating of the samples that would be returned
  - We have the experience and techniques
  - We have the analytical sensitivity and precision
  - We will have the samples (rocklets, in the thousands)
  - We will be able to use routinely multiple dating techniques on the same samples and investigate age concordancy and sample complexities

MoonRise: Isotope Dating State-of-the-Art



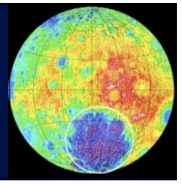
- Historical: isotope dating of lunar samples (long-lived pairs)
  - We started for Apollo samples with ^{87}Rb-^{87}Sr and ^{40}Ar-^{39}Ar
  - Developed low contamination for $^{238,\ 235}$U-$^{206,\ 207}$Pb (1973)
  - Developed ^{147}Sm-^{143}Nd (1975+)
  - Developed ^{187}Re-^{187}Os (mass spec 1990; chemistry 1996)
- Precision
  - **Apollo (during the missions)** 100-50 ppm for TIMS
  - **Now** 10 ppm for MC-TIMS and MC-ICP-MS
  - **Now** improved by simultaneous ion collection (the MC part!) and not requiring very stable ion beams for time interpolation to determine isotope ratios
  - **Now** a factor of 10 improvement in duty cycle (better sensitivity)
- **Expected age precision 5-10 Ma (1-2 ‰)**

MoonRise: Returned Sample Plan



- Curation of the returned samples within the pristine Lunar Curatorial Facility at JSC
- Preliminary Examination of returned samples, within the pristine Lunar Curatorial Facility, by the MoonRise Science Team and Lunar Curatorial personnel
- Unique samples and large (1-2 cm) samples will be analyzed in a consortium mode, to maximize science return
- For age dating, the plan is to obtain ages by multiple techniques on the same samples, in order to identify concordancy and reliability of age determinations
- Samples will be available to the scientific community, for general scientific research, with sample allocations through CAPTEM, following the concepts and procedures for maximizing science return and preserving samples, as for Apollo samples

MoonRise: Isotope Dating



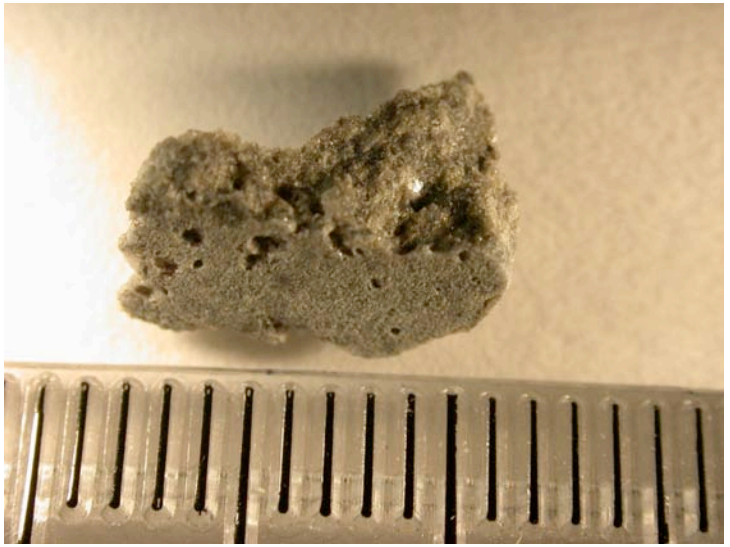
- For internal isochron determinations and potentially for ^{40}Ar-^{39}Ar dating
  - Binocular examination of the sample, petrographic examination of a thin section, and preliminary chemical composition of major and minor elements
  - Whole rock and mineral separates, obtained by standard techniques (crushing, handpicking of crystals, plus magnetic and density separations of minerals)
  - Parent and daughter elements chemically separated to eliminate interferences
  - Isotope ratios determined to the highest precision available by mass spectrometry
- These techniques are well developed and are applied routinely, even for small samples

MoonRise: Test of Analytical Procedures

Two Apollo 16 impact melt rocks (VHA-type) were processed and analyzed for Rb-Sr, at JSC

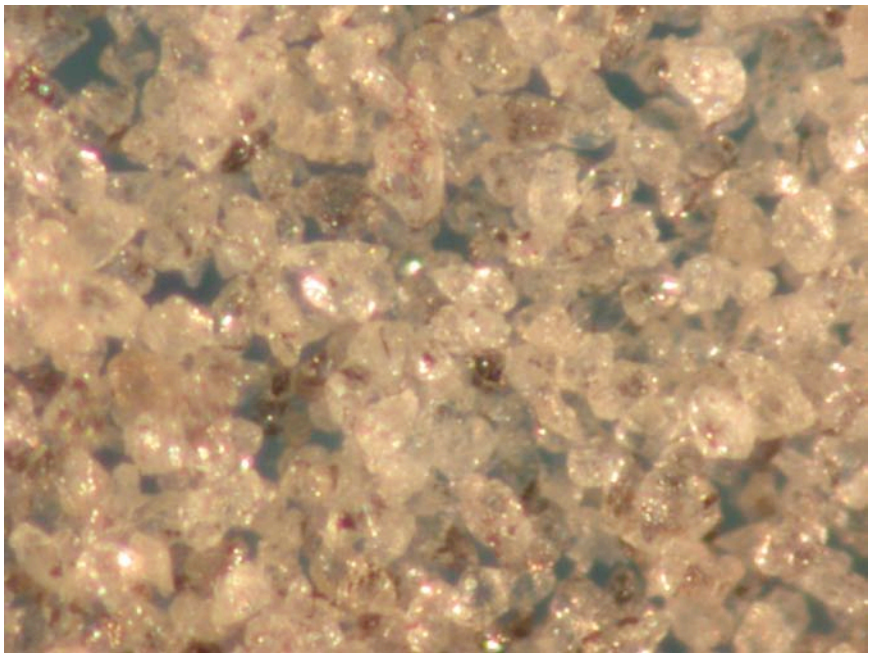
- Rb-Sr work completed on one of the rocks
- Sm-Nd work in progress

- 63545: 255 mg processed
  - Whole rock and mineral separates measurements
- 60335 300: mg processed
  - Whole rock Rb-Sr measurements obtained up to now



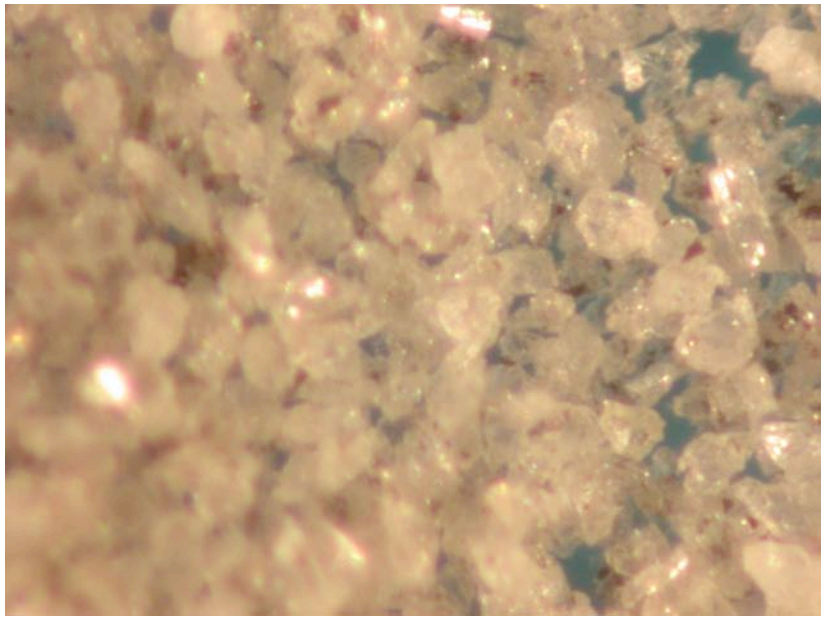
60335 sample chip
mm scale is shown

Apollo 16 VHA basalt 63545

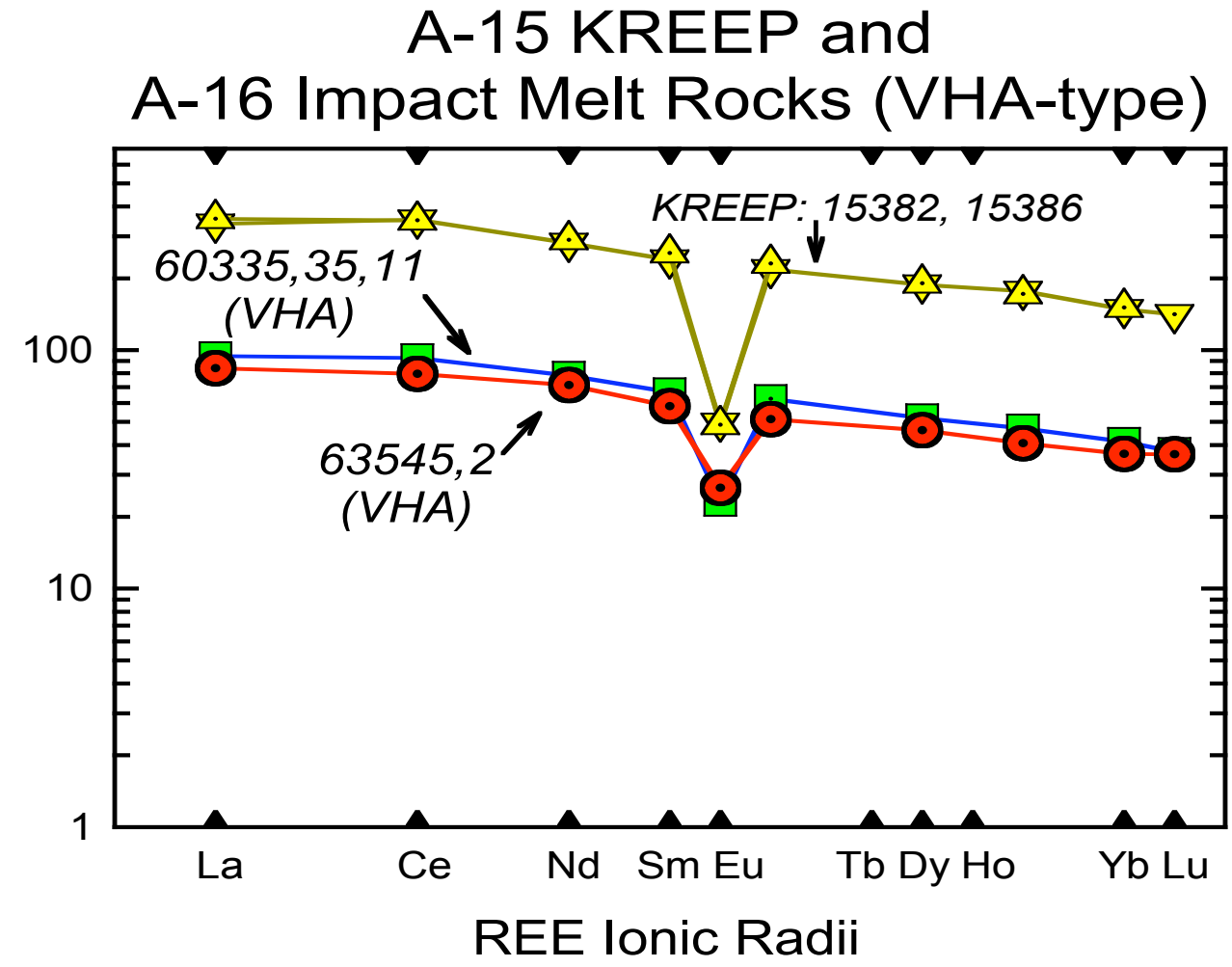


Pyroxene separate
60-44 microns

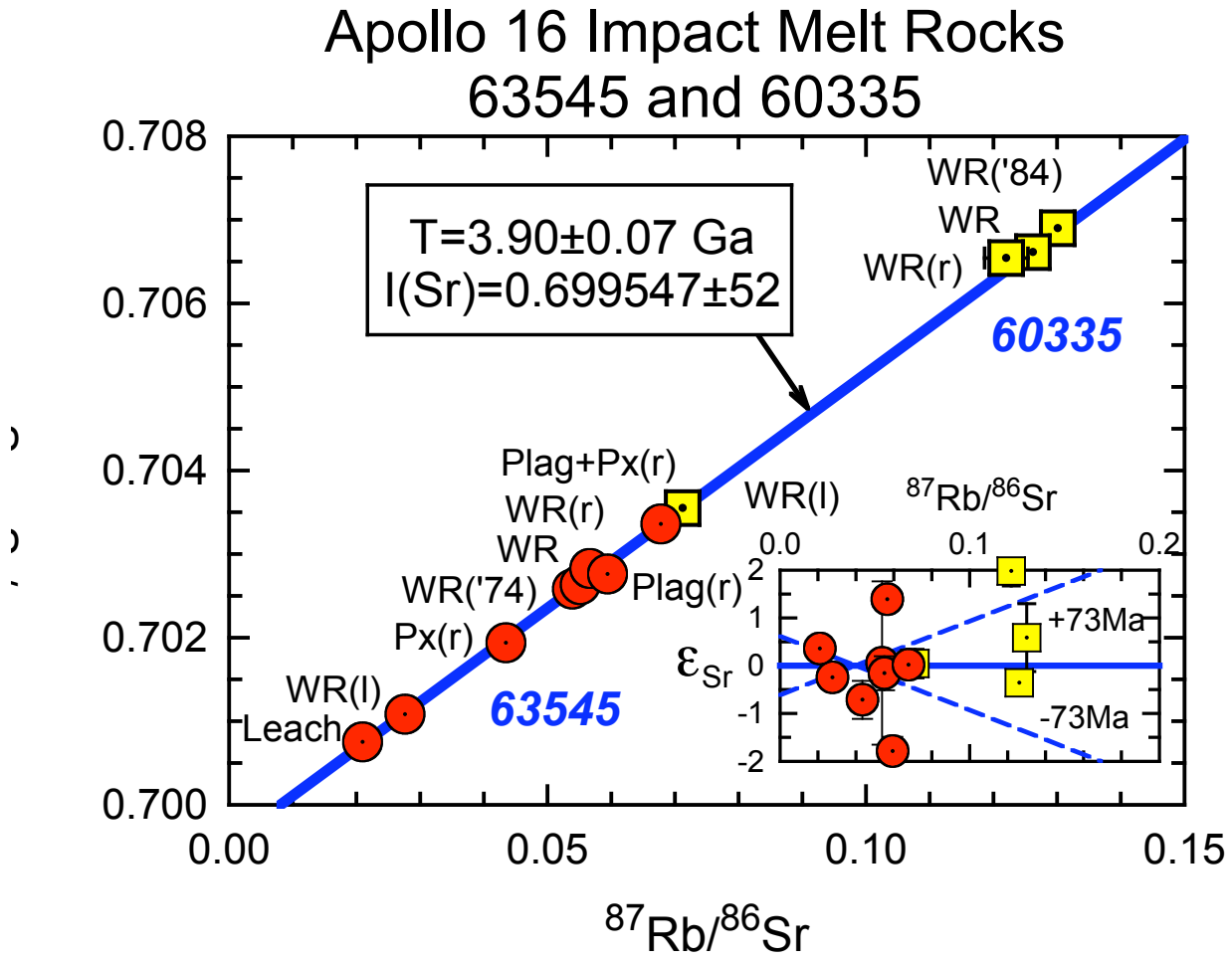
Plagioclase separate
60-44 microns



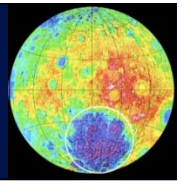
MoonRise: Comparison of VHA and KREEP

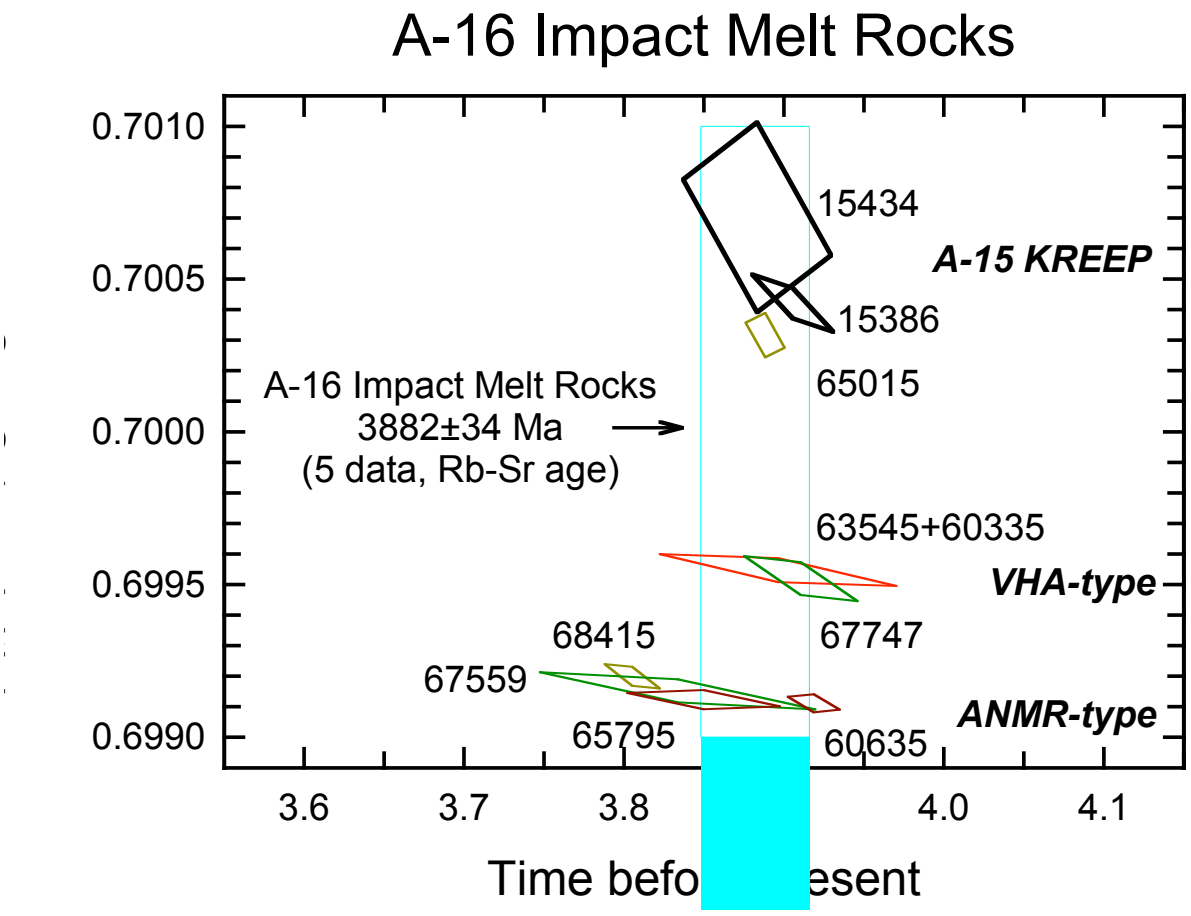


MoonRise: Test Internal Isochron



MoonRise: Initial Sr Indicate Level of KREEP

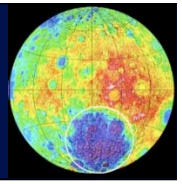




Ages on small, test rock chips are in agreement with results on large samples

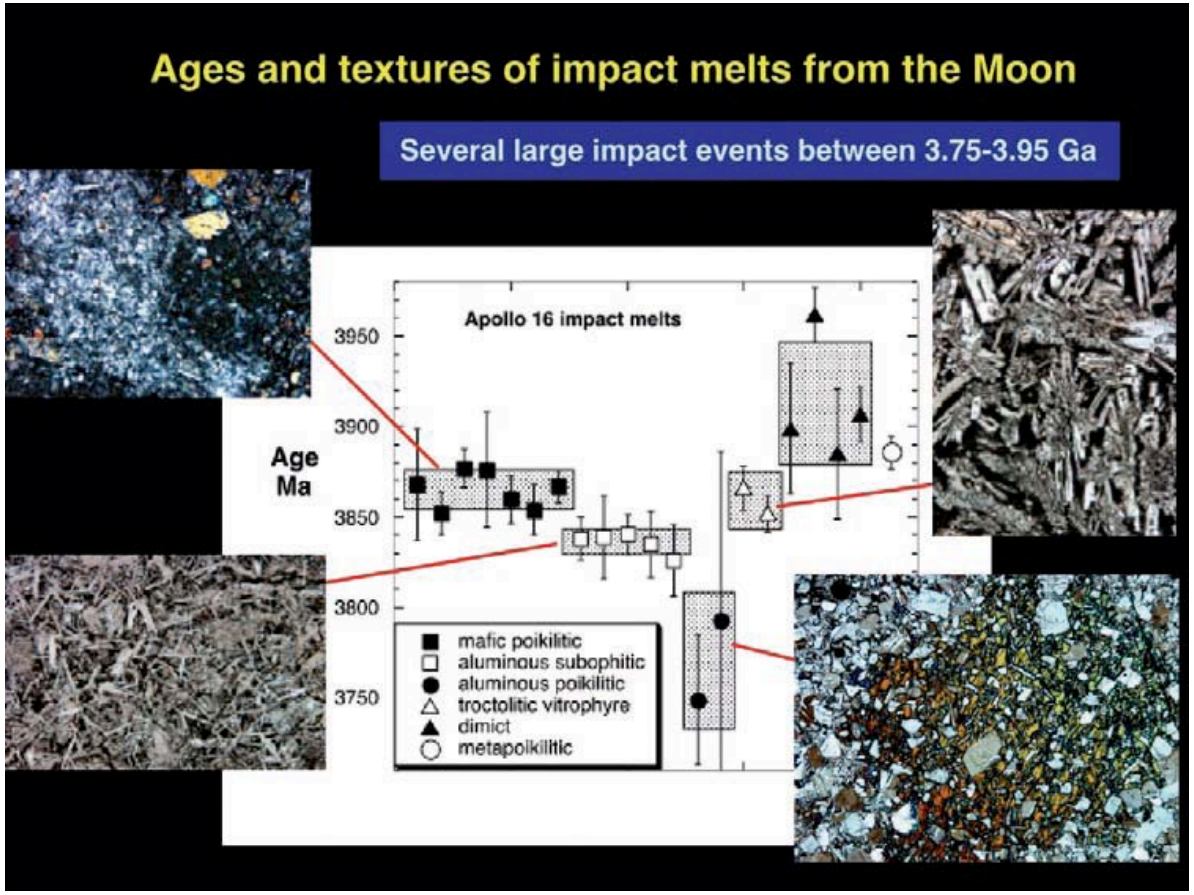
The range in Initial $^{87}Sr/^{86}Sr$ is a measure of the level of KREEP abundances
All ages fall in a narrow interval of 3.85-3.92 Ma

MoonRise: ^{40}Ar-^{39}Ar Ages on Apollo 16 Impact Melts



Ar-Ar ages on rock micro chips (each weighing 1-2 mg) of Apollo 16 impact melt breccias

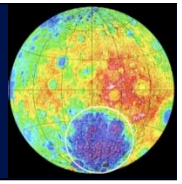
Ranges of Rb-Sr and ^{40}Ar-^{39}Ar ages agree



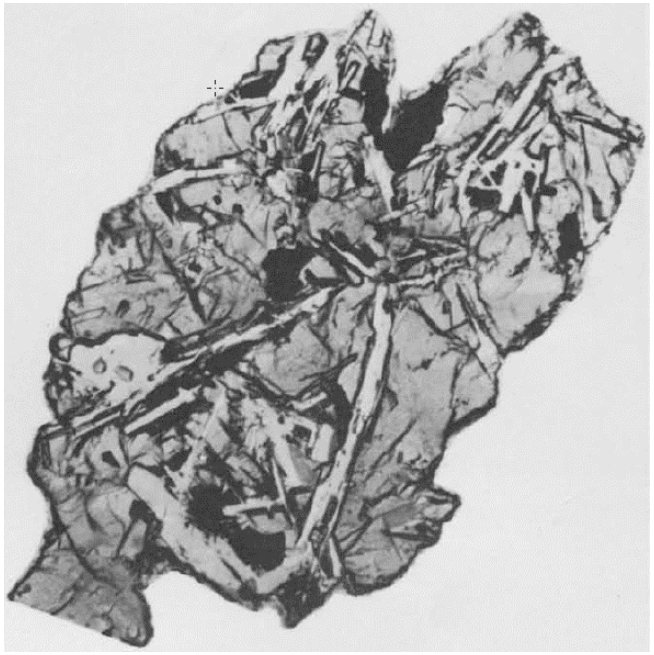
- Proposed groupings of Apollo 16 impact melt breccias based on textures and ages
- The groups probably represent different impact events between 3.75 and 3.95 Ga
- Photomicrographs of the rock textures are shown using an optical microscope
- Field of view for the photomicrographs is 1 × 2 mm for each sample

Marc Norman (2009) in Elements

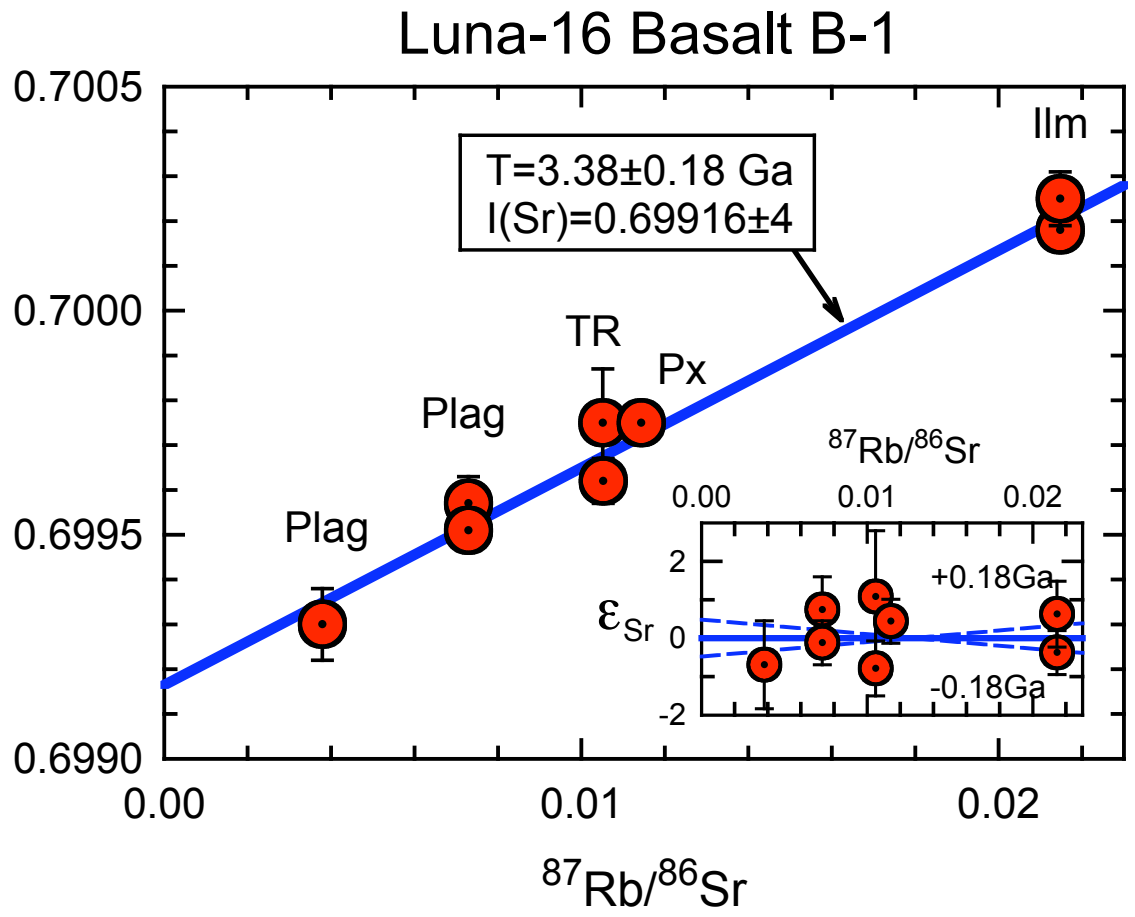
MoonRise: Smaller samples from the past



Luna 16 example, 62 mg



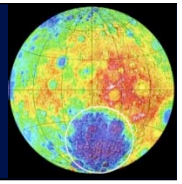
Fine grained ophitic basalt
(cpx 50%; plag 40%; ilm 7%)
0.5 mm total size



A 62 mg basalt “boulder”, with a thin glaze;
3 mg for TR, 46 mg for mineral separations,
9 mg for ^{39}Ar-^{40}Ar

Papanastassiou and Wasserburg (1972) EPSL **13**, 368-374.

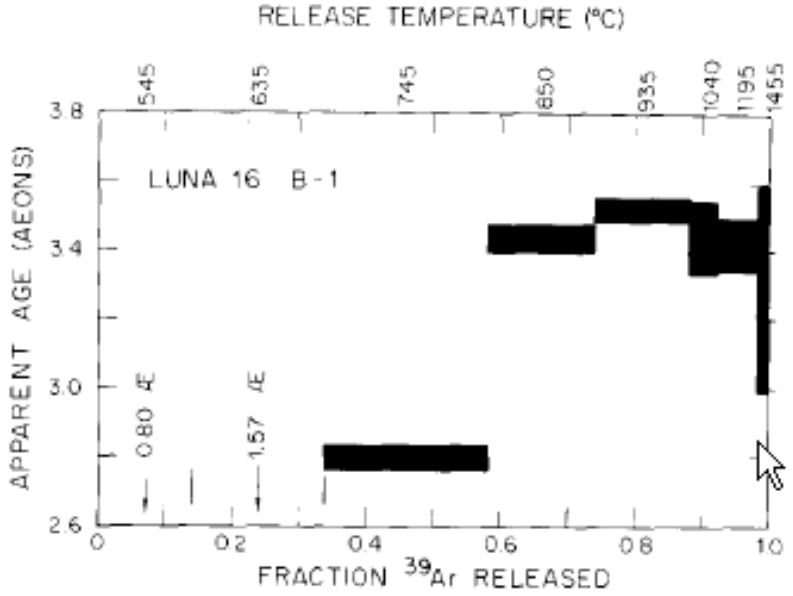
MoonRise: Luna 16 Rb-Sr and Ar-Ar agree



Luna 16, continued

Rb-Sr and ^{40}Ar-^{39}Ar ages on the Luna 16 Basalt are in agreement

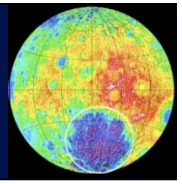
J.C. Huneke et al., Age determinations of basalt from Mare Fecunditatis



Luna 16 Basalt B-1 (2 chips, 9 mg total) shows large low temperature ^{40}Ar loss, but ^{40}Ar-^{39}Ar defines a good high temperature age of 3.45±0.04 Ga

Huneke, Podosek, and Wasserburg (1972) EPSL **13**, 375-383.

MoonRise: More small samples from the past

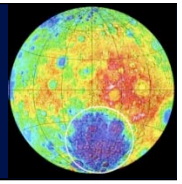


Luna 24 Example

- Luna 24, 24170,1, microgabbro, a layer, within the returned Luna 24 core
- 96 mg of chips allocated for a Consortium study by Roman Schmitt, Ed Anders, and the Lunatic Asylum
- Lunatic Asylum work
  - Contributing members: Wasserburg, Radicati di Brozolo, Papanastassiou, McCulloch, Huneke, Dymek, DePaolo, Chodos, Albee
  - Published, 1978, in Mare Crisium, Merrill and Papike Ed., Pergamon Press, pp. 657-678.
  - Petrology, mineralogy, chemistry, age dating, neutron capture effects
  - **Age dating using three techniques -- Rb-Sr, Sm-Nd, ^{40}Ar-^{39}Ar**
  - Sample augmented to 130 mg with fine powder from 24170,0, for mineral separations, based on low Nd content of plagioclase
  - Neutron capture exposure age

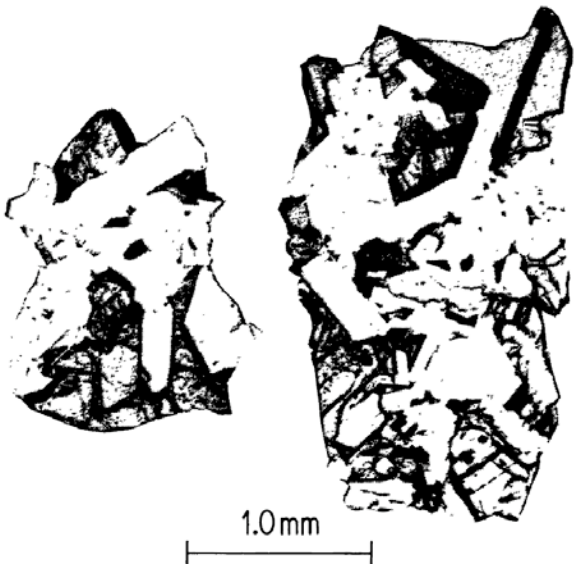
Why show Luna 16 and 20 data: when the samples are rare and extremely small, the techniques must work and do work!

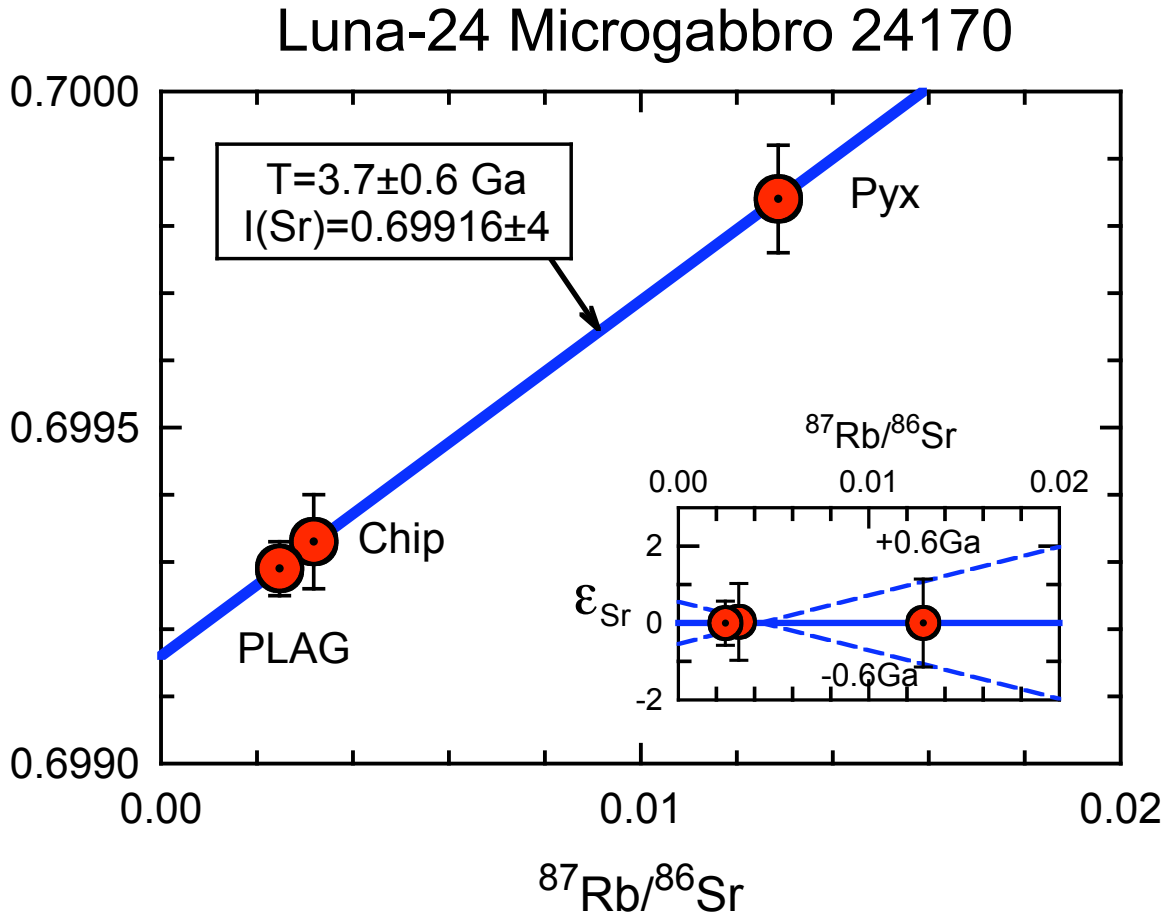
MoonRise: Luna 24 Rb-Sr age



Luna 24 example

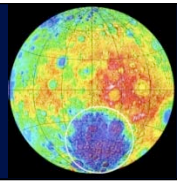
Photomicrographs of two chips of 24170

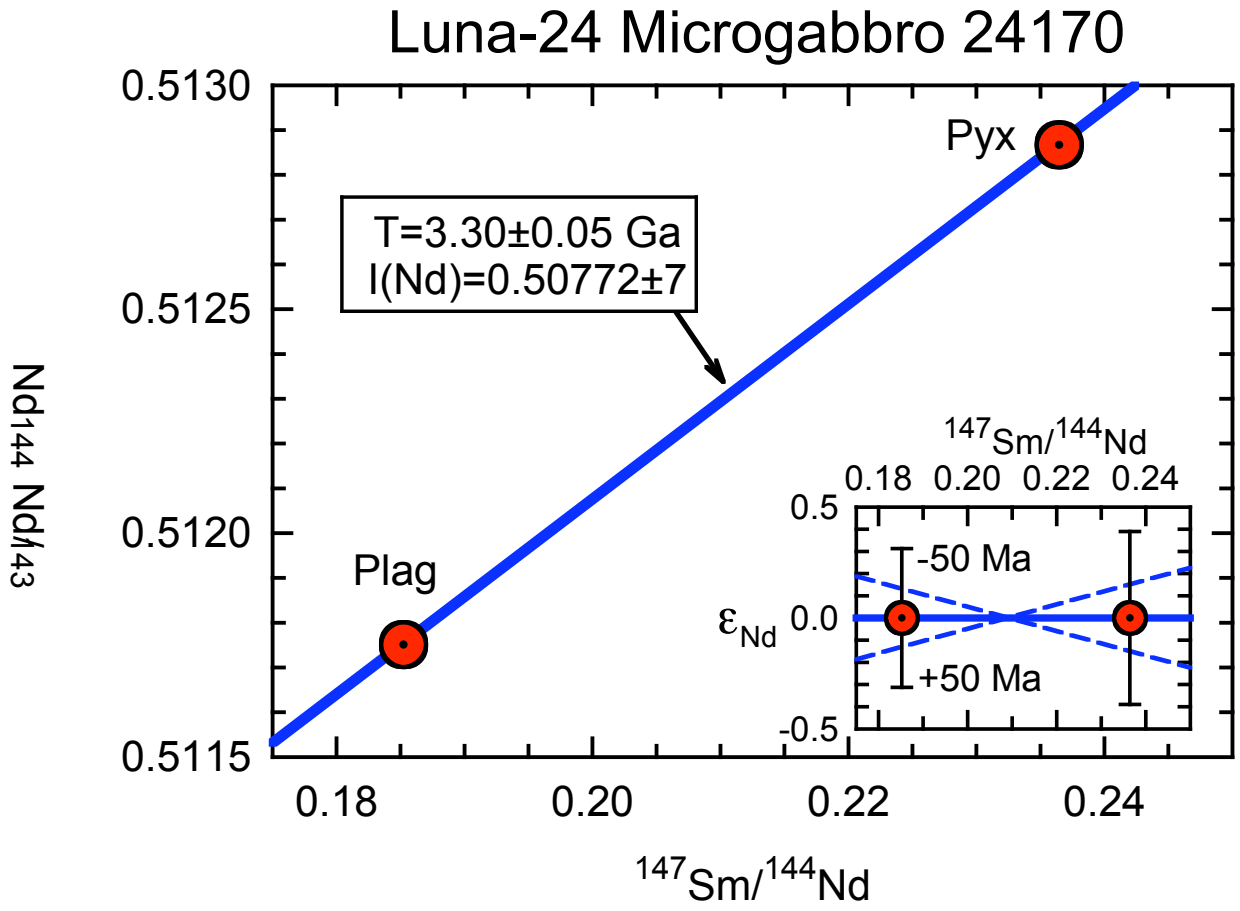




The Lunatic Asylum, 1978

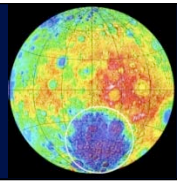
MoonRise: Luna 24 Sm-Nd age

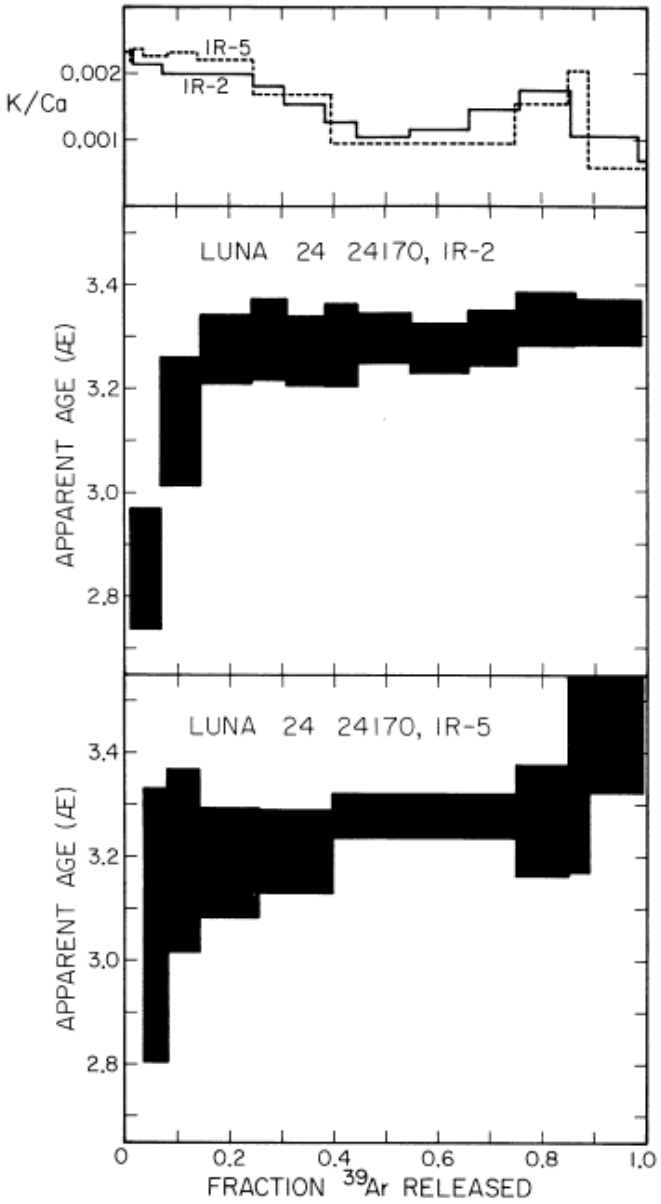




The Lunatic Asylum, 1978

MoonRise: Luna 24 Ar-Ar age





^{40}Ar-^{39}Ar on two chips (0.9 and 0.4 mg) of the Luna 24 gabbro

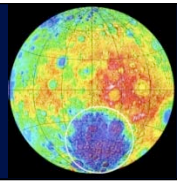
Identical ages of 3.30±0.04 AE for both fragments

Consistent ages were obtained by all three dating techniques, Rb-Sr, Sm-Nd, and Ar-Ar, although Rb-Sr was much less precise, due to very low Rb/Sr

c

The Lunatic Asylum, 1978

MoonRise: Isotope Dating Conclusions



- The analytical techniques are well developed, with excellent sensitivity and precision
- Isotope dating, by multiple techniques, for each individual rocklet, is feasible and is coupled with studies of petrology, mineralogy, chemistry, exposure ages
- Thousands of rocklets would be returned and used by the MoonRise Team, by Participating Scientists, by the international community, and by future generations
- Addressing the Lunar Terminal Cataclysm hypothesis and the Nice model for the Solar System evolution would become a reality, if the mission is selected
- No “downside”, even given the possible complexity of SPA samples